5. Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes. This chapter provides an assessment of non-carbon dioxide emissions from the following source categories: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, and field burning of agricultural residues (see Figure 5-1). Carbon dioxide (CO_2) emissions and removals from agriculture-related land-use activities, such as conversion of grassland to cultivated land, are discussed in the Land-Use Change and Forestry chapter. Carbon dioxide emissions from on-farm energy use are accounted in the Energy chapter.

Figure 5-1: 2001 Agriculture Chapter GHG Sources

In 2001, agricultural activities were responsible for emissions of 474.9 Tg CO_2 Eq., or 6.8 percent of total U.S. greenhouse gas emissions. Methane (CH_4) and nitrous oxide (N_2O) were the primary greenhouse gases emitted by agricultural activities. Methane emissions from enteric fermentation and manure management represent about 19 percent and 6 percent of total CH_4 emissions from anthropogenic activities, respectively. Of all domestic animal types, beef and dairy cattle were by far the largest emitters of CH_4. Rice cultivation and agricultural crop residue burning were minor sources of CH_4. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions, accounting for 69 percent. Manure management and field burning of agricultural residues were also small sources of N_2O emissions.

Table 5-1 and Table 5-2 present emission estimates for the Agriculture chapter. Between 1990 and 2001, CH_4 emissions from agricultural activities increased by 3.3 percent while N_2O emissions increased by 10.1 percent. In addition to CH_4 and N_2O, field burning of agricultural residues was also a minor source of the ambient air pollutants carbon monoxide (CO) and nitrogen oxides (NO_x).

Table 5-1: Emissions from Agriculture (Tg CO_2 Eq.)

Gas/Source	1990	1995	1996	1997	1998	1999	2000	2001
CH_4	**156.9**	**167.4**	**163.1**	**163.1**	**164.4**	**164.5**	**162.2**	**162.1**
Enteric Fermentation	117.9	123.0	120.5	118.3	116.7	116.6	115.7	114.8
Manure Management	31.3	36.2	34.9	36.6	39.0	38.9	38.2	38.9
Rice Cultivation	7.1	7.6	7.0	7.5	7.9	8.3	7.5	7.6
Field Burning of Agricultural Residues	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8
N_2O	**284.1**	**301.0**	**310.6**	**315.9**	**316.9**	**314.8**	**312.9**	**312.8**
Agricultural Soil Management	267.5	284.1	293.2	298.2	299.2	297.0	294.6	294.3
Manure Management	16.2	16.6	17.0	17.3	17.3	17.4	17.9	18.0
Field Burning of Agricultural Residues	0.4	0.4	0.4	0.4	0.5	0.4	0.5	0.5
Total	**441.0**	**468.4**	**473.7**	**479.0**	**481.3**	**479.3**	**475.1**	**474.9**

Note: Totals may not sum due to independent rounding.

Table 5-2: Emissions from Agriculture (Gg)

Gas/Source	1990	1995	1996	1997	1998	1999	2000	2001
CH_4	**7,473**	**7,972**	**7,765**	**7,768**	**7,829**	**7,834**	**7,723**	**7,718**
Enteric Fermentation	5,612	5,855	5,737	5,635	5,557	5,551	5,509	5,468
Manure Management	1,490	1,723	1,661	1,741	1,858	1,852	1,820	1,850
Rice Cultivation	339	363	332	356	376	395	357	364
Field Burning of Agricultural Residues	33	31	36	36	37	36	37	36
N_2O	**916**	**971**	**1,002**	**1,019**	**1,022**	**1,015**	**1,009**	**1,009**
Agricultural Soil Management	863	916	946	962	965	958	950	949

Manure Management	52		53	55	56	56	56	58	58
Field Burning of Agricultural Residues	1		1	1	1	1	1	1	1

Note: Totals may not sum due to independent rounding.

Enteric Fermentation

Methane is produced as part of normal digestive processes in animals. During digestion, microbes resident in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process, referred to as enteric fermentation, produces CH_4 as a by-product, which can be exhaled or eructated by the animal. The amount of CH_4 produced and excreted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes.

Among domesticated animal types, ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of CH_4 because of their unique digestive system. Ruminants possess a rumen, or large "fore-stomach," in which microbial fermentation breaks down the feed they consume into products that can be metabolized. The microbial fermentation that occurs in the rumen enables them to digest coarse plant material that non-ruminant animals cannot. Ruminant animals, consequently, have the highest CH_4 emissions among all animal types.

Non-ruminant domesticated animals (e.g., swine, horses, and mules) also produce CH_4 emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine. These non-ruminants emit significantly less CH_4 on a per-animal basis than ruminants because the capacity of the large intestine to produce CH_4 is lower.

In addition to the type of digestive system, an animal's feed quality and feed intake also affects CH_4 emissions. In general, a lower feed quality and a higher feed intake leads to higher CH_4 emissions. Feed intake is positively related to animal size, growth rate, and production (e.g., milk production, wool growth, pregnancy, or work). Therefore, feed intake varies among animal types as well as among different management practices for individual animal types.

Methane emission estimates from enteric fermentation are provided in Table 5-3 and Table 5-4. Total livestock CH_4 emissions in 2001 were 114.8 Tg CO_2 Eq. (5,468 Gg), decreasing slightly since 2000 due to minor decreases in animal populations. Beef cattle remain the largest contributor of CH_4 emissions from enteric fermentation, accounting for 72 percent in 2001. Emissions from dairy cattle in 2001 accounted for 23 percent, and the remaining 5 percent was from horses, sheep, swine, and goats.

From 1990 to 2001, emissions from enteric fermentation have decreased by 3 percent. Generally, emissions have been decreasing since 1995, mainly due to decreasing populations of both beef and dairy cattle and improved feed quality for feedlot cattle. During this timeframe, populations of sheep and goats have also decreased, while horse populations increased and the populations of swine fluctuated.

Table 5-3: CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq.)

Livestock Type	**1990**		**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Beef Cattle	83.2		89.7	88.8	86.6	85.0	84.7	83.5	82.7
Dairy Cattle	28.9		27.7	26.3	26.4	26.3	26.6	27.0	26.9
Horses	1.9		1.9	1.9	2.0	2.0	2.0	2.0	2.0
Sheep	1.9		1.5	1.4	1.3	1.3	1.2	1.2	1.2
Swine	1.7		1.9	1.8	1.8	2.0	1.9	1.9	1.9
Goats	0.3		0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total	**117.9**		**123.0**	**120.5**	**118.3**	**116.7**	**116.6**	**115.7**	**114.8**

Note: Totals may not sum due to independent rounding.

Table 5-4: CH_4 Emissions from Enteric Fermentation (Gg)

Livestock Type	1990		1995	1996	1997	1998	1999	2000	2001
Beef Cattle	3,961		4,272	4,227	4,124	4,046	4,035	3,976	3,936
Dairy Cattle	1,375		1,320	1,254	1,255	1,251	1,266	1,284	1,282
Horses	91		92	93	93	94	93	94	95
Sheep	91		72	68	64	63	58	56	56
Swine	81		88	84	88	93	90	88	88
Goats	13		11	10	10	10	10	10	10
Total	**5,612**		**5,855**	**5,737**	**5,635**	**5,557**	**5,551**	**5,509**	**5,468**

Note: Totals may not sum due to independent rounding.

Methodology

Livestock emission estimates fall into two categories: cattle and other domesticated animals. Cattle, due to their large population, large size, and particular digestive characteristics, account for the majority of CH_4 emissions from livestock in the United States. Cattle production systems in the United States are better characterized in comparison with other livestock production systems. A more detailed methodology (i.e., IPCC Tier 2) was therefore applied to estimating emissions for cattle. Emission estimates for other domesticated animals were handled using a less detailed approach (i.e., IPCC Tier 1).

While the large diversity of animal management practices cannot be precisely characterized and evaluated, significant scientific literature exists that describes the quantity of CH_4 produced by individual ruminant animals, particularly cattle. A detailed model that incorporates this information and other analyses of livestock population, feeding practices and production characteristics was used to estimate emissions from cattle populations.

National cattle population statistics were disaggregated into the following cattle sub-populations:

Dairy Cattle
- Calves
- Heifer Replacements
- Cows

Beef Cattle
- Calves
- Heifer Replacements
- Heifer and Steer Stockers
- Animals in Feedlots
- Cows
- Bulls

Calf birth estimates, end of year population statistics, detailed feedlot placement information, and slaughter weight data were used in the model to initiate and track cohorts of individual animal types having distinct emissions profiles. The key variables tracked for each of the cattle population categories are described in Annex L. These variables include performance factors such as pregnancy and lactation as well as average weights and weight gain.

Diet characteristics were estimated by region for U.S. dairy, beef, and feedlot cattle. These estimates were used to calculate Digestible Energy (DE) values and CH_4 conversion rates (Y_m) for each population category. The IPCC recommends Y_m values of 3.5 to 4.5 percent for feedlot cattle and 5.5 to 6.5 percent for all other cattle. Given the availability of detailed diet information for different regions and animal types in the United States, DE and Y_m values unique to the United States were developed, rather than using the recommended IPCC values. The diet characterizations and estimation of DE and Y_m values were based on contact with state agricultural extension specialists, a review of published forage quality studies, expert opinion, and modeling of animal physiology. See Annex L for more details on the method used to characterize cattle diets in the United States.

In order to estimate CH_4 emissions from cattle, the population was divided into region, age, sub-type (e.g., calves, heifer replacements, cows, etc.), and production (i.e., pregnant, lactating, etc.) groupings to more fully capture differences in CH_4 emissions from these animal types. Cattle diet characteristics were used to develop regional emission factors for each sub-category. Tier 2 equations from IPCC (2000) were used to produce CH_4 emission factors for the following cattle types: dairy cows, beef cows, dairy replacements, beef replacements, steer stockers, heifer stockers, steer feedlot animals, and heifer feedlot animals. To estimate emissions from cattle, population data were multiplied by the emission factor for each cattle type. More details are provided in Annex L.

Emission estimates for other animal types were based on average emission factors representative of entire populations of each animal type. Methane emissions from these animals accounted for a minor portion of total CH_4 emissions from livestock in the United States from 1990 through 2001. Also, the variability in emission factors for each of these other animal types (e.g. variability by age, production system, and feeding practice within each animal type) is less than that for cattle.

See Annex L for more detailed information on the methodology and data used to calculate CH_4 emissions from enteric fermentation.

Data Sources

Annual cattle population data were obtained from the U.S. Department of Agriculture's National Agricultural Statistics Service (1995a,b, 1999a,c,d,f, 2000a,c,d,f, 2001a,c,d,f, 2002a,c,d,f). Diet characteristics were used to develop DE and Y_m values for cattle populations. Diet characteristics for dairy cattle were from Donovan (1999), while beef cattle were derived from NRC (2000). DE and Y_m for dairy cows were calculated from diet characteristics using a model simulating ruminant digestion in growing and/or lactating cattle (Donovan and Baldwin 1999). For feedlot animals, DE and Y_m values recommended by Johnson (1999) were used. Values from EPA (1993) were used for dairy replacement heifers. For grazing beef cattle, DE values were based on diet information in NRC (2000) and Y_m values were based on Johnson (2002). Weight data were estimated from Feedstuffs (1998), Western Dairyman (1998), and expert opinion. Annual livestock population data for other livestock types, except horses, as well as feedlot placement information were obtained from the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA 1994a-b, 1998, 1999b,e, 2000b,e, 2001b,e, 2002b,e). Horse data were obtained from the Food and Agriculture Organization (FAO) statistical database (FAO 2002). Methane emissions from sheep, goats, swine, and horses were estimated by using emission factors utilized in Crutzen et al. (1986, cited in IPCC/UNEP/OECD/IEA 1997). These emission factors are representative of typical animal sizes, feed intakes, and feed characteristics in developed countries. The methodology is the same as that recommended by IPCC (IPCC/UNEP/OECD/IEA 1997, IPCC 2000).

Uncertainty

The basic uncertainties associated with estimating emissions from enteric fermentation are the range of emission factors possible for the different animal types and the number of animals with a particular emissions profile that exist during the year. Although determining an emission factor for all possible cattle sub-groupings and diet characterizations in the United States is not possible, the enteric fermentation model that was used estimates the likely emission factors for the major animal types and diets. The model generates estimates for dairy and beef cows, dairy and beef replacements, beef stockers, and feedlot animals. The analysis departs from the recommended IPCC (2000) DE and Y_m values to account for diets for these different animal types regionally. Based on expert opinion and peer reviewer recommendations, the values supporting the development of emission factors for the animal types studied are more appropriate for the situation in the United States than the IPCC recommended values.

In addition to the uncertainty associated with developing emission factors for different cattle population categories based on estimated energy requirements and diet characterizations, there is uncertainty in the estimation of animal populations by animal type. The model estimates the movement of animal cohorts through the various monthly age and weight classes by animal type. Several inputs affect the precision of this approach, including estimates of births by month, weight gain of animals by age class, and placement of animals into feedlots based on placement statistics and slaughter weight data. However, the model characterizes the changes in U.S. cattle population and captures potential differences related to the emission factors used for different animal types.

The values for Y_m and DE reflect the diet characterizations that are assumed for each cattle group, within each region of the country. While these values try to reflect the general diet characteristics within each region, there is uncertainty associated with local variations in feed and in the way cattle feed intake is managed.

In order to ensure the quality of the emission estimates from enteric fermentation, the IPCC Tier 1 and Tier 2 QA/QC procedures were implemented. Tier 1 procedures included quality checks on data gathering, input, and documentation, as well as checks on the actual emission calculations. Additionally, Tier 2 procedures included quality checks on emission factors, activity data, and emissions.

Manure Management

The management of livestock manure can produce anthropogenic CH_4 and N_2O emissions. Methane is produced by the anaerobic decomposition of manure. Nitrous oxide is produced as part of the nitrogen cycle through the nitrification and denitrification of the organic nitrogen in livestock manure and urine.

When livestock or poultry manure are stored or treated in systems that promote anaerobic conditions (e.g., as a liquid/slurry in lagoons, ponds, tanks, or pits), the decomposition of materials in the manure tends to produce CH_4. When manure is handled as a solid (e.g., in stacks or pits) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce little or no CH_4. A number of other factors related to how the manure is handled also affect the amount of CH_4 produced. Ambient temperature, moisture, and manure storage or residency time affect the amount of CH_4 produced because they influence the growth of the bacteria responsible for CH_4 formation. For example, CH_4 production generally increases with rising temperature and residency time. Also, for non-liquid based manure systems, moist conditions (which are a function of rainfall and humidity) favor CH_4 production. Although the majority of manure is handled as a solid, producing little CH_4, the general trend in manure management, particularly for large dairy and swine producers, is one of increasing use of liquid systems. In addition, use of daily spread systems at smaller dairies is decreasing, due to new regulations limiting the application of manure nutrients, which has resulted in an increase of manure managed and stored on site at these smaller dairies.

The composition of the manure also affects the amount of CH_4 produced. Manure composition varies by animal type, including the animal's digestive system and diet. In general, the greater the energy content of the feed, the greater the potential for CH_4 emissions. For example, feedlot cattle fed a high-energy grain diet generate manure with a high CH_4-producing capacity. Range cattle fed a low energy diet of forage material produce manure with about 50 percent of the CH_4-producing potential of feedlot cattle manure. However, some higher energy feeds also are more digestible than lower quality forages, which can result in less overall waste excreted from the animal. Ultimately, a combination of diet characteristics and the growth rate of the animals will affect the total manure produced.

A very small portion of the total nitrogen excreted is expected to convert to N_2O in the waste management system. The production of N_2O from livestock manure depends on the composition of the manure and urine, the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system. For N_2O emissions to occur, the manure must first be handled aerobically where ammonia or organic nitrogen is converted to nitrates and nitrites (nitrification), and then handled anaerobically where the nitrates and nitrites are reduced to nitrogen gas (N_2), with intermediate production of N_2O and nitric oxide (NO) (denitrification) (Groffman, et al. 2000). These emissions are most likely to occur in dry manure handling systems that have aerobic conditions, but that also contain pockets of anaerobic conditions due to saturation. For example, manure at cattle drylots is deposited on soil, oxidized to nitrite and nitrate, and has the potential to encounter saturated conditions following rain events.

Certain N_2O emissions are accounted for and discussed under Agricultural Soil Management. These are emissions from livestock manure and urine deposited on pasture, range, or paddock lands, as well as emissions from manure and urine that is spread onto fields either directly as "daily spread" or after it is removed from manure management systems (e.g., lagoon, pit, etc.).

Table 5-5 and Table 5-6 provide estimates of CH_4 and N_2O emissions from manure management by animal category. Estimates for CH_4 emissions in 2001 were 38.9 Tg CO_2 Eq. (1,850 Gg), 24 percent higher than in 1990.

The majority of this increase was from swine and dairy cow manure, which increased 31 and 32 percent respectively, and is attributed to shifts by the swine and dairy industries towards larger facilities. Larger swine and dairy farms tend to use liquid systems to manage (flush or scrape) and store manure. Thus the shift towards larger facilities is translated into an increasing use of liquid manure management systems. This shift was accounted for by incorporating state-specific weighted CH_4 conversion factor (MCF) values calculated from the 1992 and 1997 farm-size distribution reported in the *Census of Agriculture* (USDA 1999e). From 2000 to 2001, there was a 1.8 percent increase in CH_4 emissions, due to minor shifts in the animal populations.

As stated previously, smaller dairies are moving away from daily spread systems. Therefore, more manure is managed and stored on site, contributing to additional CH_4 emissions over the time series. A description of the emission estimation methodology is provided in Annex M.

Total N_2O emissions from manure management systems in 2001 were estimated to be 18.0 Tg CO_2 Eq. (58.0 Gg). The 11 percent increase in N_2O emissions from 1990 to 2001 can be partially attributed to a shift in the poultry industry away from the use of liquid manure management systems, in favor of litter-based systems and high rise houses. In addition, there was an overall increase in the population of poultry and swine from 1990 to 2001, although swine populations declined slightly in 1993, 1995, 1996, 1999, and 2000 from previous years and poultry populations decreased in 1995 and 2001 from previous years. Nitrous oxide emissions showed a 0.6 percent increase from 2000 to 2001, due to minor shifts in animal population.

The population of beef cattle in feedlots, which tend to store and manage manure on site, also increased, resulting in increased N_2O emissions from this animal category. Although dairy cow populations decreased overall, the population of dairies managing and storing manure on site—as opposed to using pasture, range, or paddock or daily spread systems—increased. Therefore, the increase in dairies using on-site storage to manage their manure results in a steady level of N_2O emissions. As stated previously, N_2O emissions from livestock manure deposited on pasture, range, or paddock land and manure immediately applied to land in daily spread systems are accounted for under Agricultural Soil Management.

Table 5-5: CH_4 and N_2O Emissions from Manure Management (Tg CO_2 Eq.)

Gas/Animal Type	1990		1995	1996	1997	1998	1999	2000	2001
CH_4	**31.3**		**36.2**	**34.9**	**36.6**	**39.0**	**38.9**	**38.2**	**38.9**
Dairy Cattle	11.4		13.4	12.8	13.4	13.9	14.7	14.6	15.1
Beef Cattle	3.4		3.5	3.5	3.4	3.3	3.3	3.3	3.3
Swine	13.1		16.0	15.3	16.4	18.4	17.6	17.1	17.1
Sheep	0.1		0.1	+	+	+	+	+	+
Goats	+		+	+	+	+	+	+	+
Poultry	2.7		2.6	2.6	2.7	2.7	2.6	2.6	2.7
Horses	0.6		0.6	0.6	0.6	0.6	0.6	0.6	0.6
N_2O	**16.2**		**16.6**	**17.0**	**17.3**	**17.3**	**17.4**	**17.9**	**18.0**
Dairy Cattle	4.3		4.1	4.0	4.0	3.9	4.0	4.0	3.9
Beef Cattle	4.9		5.3	5.1	5.4	5.5	5.5	5.9	6.1
Swine	0.4		0.4	0.4	0.4	0.5	0.4	0.4	0.4
Sheep	+		+	+	+	+	+	+	+
Goats	+		+	+	+	+	+	+	+
Poultry	6.3		6.5	7.2	7.2	7.2	7.2	7.4	7.3
Horses	0.2		0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total	**47.5**		**52.8**	**51.9**	**53.9**	**56.3**	**56.3**	**56.1**	**56.9**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 5-6: CH_4 and N_2O Emissions from Manure Management (Gg)

Gas/Animal	1990		1995	1996	1997	1998	1999	2000	2001

Type								
CH_4	**1,490**	**1,723**	**1,661**	**1,741**	**1,858**	**1,852**	**1,820**	**1,850**
Dairy Cattle	545	640	611	639	661	700	693	719
Beef Cattle	161	164	164	161	158	158	157	155
Swine	623	763	729	781	876	838	813	815
Sheep	3	2	2	2	2	2	2	2
Goats	1	1	1	1	1	1	1	1
Poultry	128	124	125	127	130	124	125	128
Horses	29	29	29	29	30	29	30	30
N_2O	**52**	**53**	**55**	**56**	**56**	**56**	**58**	**58**
Dairy Cattle	14	13	13	13	13	13	13	13
Beef Cattle	16	17	17	17	18	18	19	20
Swine	1	1	1	1	1	1	1	1
Sheep	+	+	+	+	+	+	+	+
Goats	+	+	+	+	+	+	+	+
Poultry	21	21	23	23	23	23	24	24
Horses	1	1	1	1	1	1	1	1

+ Does not exceed 0.5 Gg
Note: Totals may not sum due to independent rounding.

Methodology

The methodologies presented in *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000) form the basis of the CH_4 and N_2O emissions estimates for each animal type. The calculation of emissions requires the following information:

- Animal population data (by animal type and state)
- Amount of nitrogen produced (amount per 1000 pound animal times average weight times number of head)
- Amount of volatile solids produced (amount per 1000 pound animal times average weight times number of head)
- Methane producing potential of the volatile solids (by animal type)
- Extent to which the CH_4 producing potential is realized for each type of manure management system (by state and manure management system)
- Portion of manure managed in each manure management system (by state and animal type)
- Portion of manure deposited on pasture, range, or paddock or used in daily spread systems

Both CH_4 and N_2O emissions were estimated by first determining activity data, including animal population, waste characteristics, and manure management system usage. For swine and dairy cattle, manure management system usage was determined for different farm size categories using data from USDA (USDA 1996b, 1998d, 2000h) and EPA (ERG 2000a, EPA 2001a, 2001b). For beef cattle and poultry, manure management system usage data was not tied to farm size (ERG 2000a, USDA 2000i). For other animal types, manure management system usage was based on previous EPA estimates (EPA 1992).

Next, MCFs and N_2O emission factors were determined for all manure management systems. MCFs for dry systems and N_2O emission factors for all systems were set equal to default IPCC factors (IPCC 2000). MCFs for liquid/slurry, anaerobic lagoon, and deep pit systems were calculated based on the forecast performance of biological systems relative to temperature changes as predicted in the van't Hoff-Arrhenius equation (see Annex M for detailed information on MCF derivations for liquid systems). The MCF calculations model the average monthly ambient temperature, a minimum system temperature, the carryover of volatile solids in the system from month to month due to long storage times exhibited by anaerobic lagoon systems, and a factor to account for management and design practices that result in the loss of volatile solids from lagoon systems.

For each animal group—except sheep, goats, and horses—the base emission factors were then weighted to incorporate the distribution of management systems used within each state and thereby to create an overall state-specific weighted emission factor. To calculate this weighted factor, the percent of manure for each animal group managed in a particular system in a state was multiplied by the emission factor for that system and state, and then summed for all manure management systems in the state.

Methane emissions were estimated using the volatile solids (VS) production for all livestock. For poultry and swine animal groups, for example, VS production was calculated using a national average VS production rate from the *Agricultural Waste Management Field Handbook* (USDA 1996a), which was then multiplied by the average weight of the animal and the state-specific animal population. For most cattle groups, regional animal-specific VS production rates that are related to the diet of the animal for each year of the inventory were used (Peterson et al., 2002). The resulting VS for each animal group was then multiplied by the maximum CH_4 producing capacity of the waste (B_o), and the state-specific CH_4 conversion factors.

Nitrous oxide emissions were estimated by determining total Kjeldahl nitrogen (TKN)[1] production for all livestock wastes using livestock population data and nitrogen excretion rates. For each animal group, TKN production was calculated using a national average nitrogen excretion rate from the *Agricultural Waste Management Field Handbook* (USDA 1996a), which was then multiplied by the average weight of the animal and the state-specific animal population. State-specific weighted N_2O emission factors specific to the type of manure management system were then applied to total nitrogen production to estimate N_2O emissions.

See Annex M for more detailed information on the methodology and data used to calculate CH_4 and N_2O emissions from manure management.

Data Sources

Animal population data for all livestock types, except horses and goats, were obtained from the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA 1994a-b, 1995a-b, 1998a-b, 1999a-c, 2000a-g, 2001a-f, 2002a-f). Horse population data were obtained from the FAOSTAT database (FAO 2002). Goat population data were obtained from the Census of Agriculture (USDA 1999d). Information regarding poultry turnover (i.e., slaughter) rate was obtained from State Natural Resource Conservation Service (NRCS) personnel (Lange 2000). Dairy cow and swine population data by farm size for each state, used for the weighted MCF and emission factor calculations, were obtained from the *Census of Agriculture*, which is conducted every five years (USDA 1999e).

Manure management system usage data for dairy and swine operations were obtained from USDA's Centers for Epidemiology and Animal Health (USDA 1996b, 1998d, 2000h) for small operations and from preliminary estimates for EPA's Office of Water regulatory effort for large operations (ERG 2000a; EPA 2001a, 2001b). Data for layers were obtained from a voluntary United Egg Producers' survey (UEP 1999), previous EPA estimates (EPA 1992), and USDA's Animal Plant Health Inspection Service (USDA 2000i). Data for beef feedlots were also obtained from EPA's Office of Water (ERG 2000a; EPA 2001a, 2001b). Manure management system usage data for other livestock were taken from previous EPA estimates (EPA 1992). Data regarding the use of daily spread and pasture, range, or paddock systems for dairy cattle were obtained from personal communications with personnel from several organizations, and data provided by those personnel (Poe et al. 1999). These organizations include state NRCS offices, state extension services, state universities, USDA National Agriculture Statistics Service (NASS), and other experts (Deal 2000, Johnson 2000, Miller 2000, Stettler 2000, Sweeten 2000, and Wright 2000). Additional information regarding the percent of beef steer and heifers on feedlots was obtained from contacts with the national USDA office (Milton 2000).

Methane conversion factors for liquid systems were calculated based on average ambient temperatures of the counties in which animal populations were located. The average county and state temperature data were obtained from the National Climate Data Center (NOAA 2001, 2002), and the county population data were based on 1992 and 1997 Census data (USDA 1999e). County population data for 1990 and 1991 were assumed to be the same as

[1] Total Kjeldahl nitrogen is a measure of organically bound nitrogen and ammonia nitrogen.

1992; county population data for 1998 through 2001 were assumed to be the same as 1997; and county population data for 1993 through 1996 were extrapolated based on 1992 and 1997 data.

The maximum CH_4 producing capacity of the volatile solids, or B_o, was determined based on data collected in a literature review (ERG 2000b). B_o data were collected for each animal type for which emissions were estimated.

Nitrogen excretion rate data from the USDA *Agricultural Waste Management Field Handbook* (USDA 1996a) were used for all livestock except sheep, goats, and horses. Data from the American Society of Agricultural Engineers (ASAE 1999) were used for these animal types. Volatile solids excretion rate data from the USDA *Agricultural Waste Management Field Handbook* (USDA 1996a) were used for swine, poultry, bulls, and calves not on feed. In addition, volatile solids production rates from Peterson et al., 2002 were used for dairy and beef cows, heifers, and steer for each year of the inventory. Nitrous oxide emission factors and MCFs for dry systems were taken from *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000).

Uncertainty

The primary factors contributing to the uncertainty in emission estimates are a lack of information on the usage of various manure management systems in each regional location and the exact CH_4 generating characteristics of each type of manure management system. Because of significant shifts in the swine and dairy sectors toward larger farms, it is believed that increasing amounts of manure are being managed in liquid manure management systems. The existing estimates reflect these shifts in the weighted MCFs based on the 1992 and 1997 farm-size data. However, the assumption of a direct relationship between farm size and liquid system usage may not apply in all cases and may vary based on geographic location. In addition, the CH_4 generating characteristics of each manure management system type are based on relatively few laboratory and field measurements, and may not match the diversity of conditions under which manure is managed nationally.

Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC 2000) published a default range of MCFs for anaerobic lagoon systems of 0 to 100 percent, which reflects the wide range in performance that may be achieved with these systems. There exist relatively few data points on which to determine country-specific MCFs for these systems. In the United States, many livestock waste treatment systems classified as anaerobic lagoons are actually holding ponds that are substantially organically overloaded and therefore not producing CH_4 at the same rate as a properly designed lagoon. In addition, these systems may not be well operated, contributing to higher loading rates when sludge is allowed to enter the treatment portion of the lagoon or the lagoon volume is pumped too low to allow treatment to occur. Rather than setting the MCF for all anaerobic lagoon systems in the United States based on data available from optimized lagoon systems, an MCF methodology was developed that more closely matches observed system performance and accounts for the affect of temperature on system performance.

However, there is uncertainty related to the new methodology. The MCF methodology used in the inventory includes a factor to account for management and design practices that result in the loss of volatile solids from the management system. This factor is currently estimated based on data from anaerobic lagoons in temperate climates, and from only three systems. However, this methodology is intended to account for systems across a range of management practices. Future work in gathering measurement data from animal waste lagoon systems across the country will contribute to the verification and refinement of this methodology. It will also be evaluated whether lagoon temperatures differ substantially from ambient temperatures and whether the lower bound estimate of temperature established for lagoons and other liquid systems should be revised for use with this methodology.

The IPCC provides a suggested MCF for poultry waste management operations of 1.5 percent. Additional study is needed in this area to determine if poultry high-rise houses promote sufficient aerobic conditions to warrant a lower MCF.

The default N_2O emission factors published in *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000) were derived using limited information. The IPCC factors are global averages; U.S.-specific emission factors may be significantly different. Manure and urine in anaerobic lagoons and liquid/slurry management systems produce CH_4 at different rates, and would in all likelihood produce N_2O at different rates, although a single N_2O emission factor was used for both system types. In addition, there are little data available to determine the extent to which nitrification-denitrification occurs in animal waste management systems. Ammonia concentrations that are present in poultry and swine systems suggest that N_2O emissions from these systems may be lower than predicted by the IPCC default factors. At this time, there are insufficient data available to develop U.S.-specific N_2O emission factors; however, this is an area of on-going research, and warrants further study as more data become available.

Although an effort was made to introduce the variability in VS production due to differences in diet for beef and dairy cows, heifers, and steer, further research is needed to confirm and track diet changes over time. A methodology to assess variability in swine volatile solids production would be useful in future inventory estimates.

Uncertainty also exists with the maximum CH_4 producing potential of volatile solids excreted by different animal groups (i.e., B_o). The B_o values used in the CH_4 calculations are published values for U.S. animal waste. However, there are several studies that provide a range of B_o values for certain animals, including dairy and swine. The B_o values chosen for dairy assign separate values for dairy cows and dairy heifers to better represent the feeding regimens of these animal groups. For example, dairy heifers do not receive an abundance of high energy feed and consequently, dairy heifer manure will not produce as much CH_4 as manure from a milking cow. However, the data available for B_o values are sparse, and do not necessarily reflect the rapid changes that have occurred in this industry with respect to feed regimens.

An uncertainty analysis was conducted on the manure management inventory considering the issues described above and based on published data from scientific and statistical literature, the IPCC, and experts in the industry. The results of the uncertainty analysis showed that the manure management CH_4 inventory has a 95 percent confidence interval of -18 percent to 20 percent around the inventory value, and the manure management N_2O inventory has a 95 percent confidence interval of -16 percent to 24 percent around the inventory value.

Rice Cultivation

Most of the world's rice, and all rice in the United States, is grown on flooded fields. When fields are flooded, aerobic decomposition of organic material gradually depletes the oxygen present in the soil and floodwater, causing anaerobic conditions in the soil to develop. Once the environment becomes anaerobic, CH_4 is produced through anaerobic decomposition of soil organic matter by methanogenic bacteria. As much as 60 to 90 percent of the CH_4 produced is oxidized by aerobic methanotrophic bacteria in the soil (Holzapfel-Pschorn et al. 1985, Sass et al. 1990). Some of the CH_4 is also leached away as dissolved CH_4 in floodwater that percolates from the field. The remaining un-oxidized CH_4 is transported from the submerged soil to the atmosphere primarily by diffusive transport through the rice plants. Minor amounts of CH_4 also escape from the soil via diffusion and bubbling through floodwaters.

The water management system under which rice is grown is one of the most important factors affecting CH_4 emissions. Upland rice fields are not flooded, and therefore are not believed to produce CH_4. In deepwater rice fields (i.e., fields with flooding depths greater than one meter), the lower stems and roots of the rice plants are dead so the primary CH_4 transport pathway to the atmosphere is blocked. The quantities of CH_4 released from deepwater fields, therefore, are believed to be significantly less than the quantities released from areas with more shallow flooding depths. Some flooded fields are drained periodically during the growing season, either intentionally or accidentally. If water is drained and soils are allowed to dry sufficiently, CH_4 emissions decrease or stop entirely. This is due to soil aeration, which not only causes existing soil CH_4 to oxidize but also inhibits further CH_4 production in soils. All rice in the United States is grown under continuously flooded conditions; none is grown under deepwater conditions. Mid-season drainage does not occur except by accident (e.g., due to levee breach).

Other factors that influence CH_4 emissions from flooded rice fields include fertilization practices (especially the use of organic fertilizers), soil temperature, soil type, rice variety, and cultivation practices (e.g., tillage, and seeding and weeding practices). The factors that determine the amount of organic material that is available to decompose (i.e., organic fertilizer use, soil type, rice variety,[2] and cultivation practices) are the most important variables influencing the amount of CH_4 emitted over an entire growing season because the total amount of CH_4 released depends primarily on the amount of organic substrate available. Soil temperature is known to be an important factor regulating the activity of methanogenic bacteria, and therefore the rate of CH_4 production. However, although temperature controls the amount of time it takes to convert a given amount of organic material to CH_4, that time is short relative to a growing season, so the dependence of total emissions over an entire growing season on soil temperature is weak. The application of synthetic fertilizers has also been found to influence CH_4 emissions; in particular, both nitrate and sulfate fertilizers (e.g., ammonium nitrate, and ammonium sulfate) appear to inhibit CH_4 formation.

Rice is cultivated in seven states: Arkansas, California, Florida, Louisiana, Mississippi, Missouri, and Texas. Soil types, rice varieties, and cultivation practices for rice vary from state to state, and even from farm to farm. However, most rice farmers utilize organic fertilizers in the form of rice residue from the previous crop, which is left standing, disked, or rolled into the fields. Most farmers also apply synthetic fertilizer to their fields, usually urea. Nitrate and sulfate fertilizers are not commonly used in rice cultivation in the United States. In addition, the climatic conditions of Arkansas, southwest Louisiana, Texas, and Florida allow for a second, or ratoon, rice crop. This second rice crop is produced from regrowth of the stubble after the first crop has been harvested. Because the first crop's stubble is left behind in ratooned fields, and there is no time delay between cropping seasons (which would allow for the stubble to decay aerobically), the amount of organic material that is available for decomposition is considerably higher than with the first (i.e., primary) crop. Methane emissions from ratoon crops have been found to be considerably higher than those from the primary crop.

Rice cultivation is a small source of CH_4 in the United States (Table 5-7 and Table 5-8). In 2001, CH_4 emissions from rice cultivation were 7.6 Tg CO_2 Eq. (364 Gg). Although annual emissions fluctuated unevenly between the years 1990 and 2001, ranging from an annual decrease of 11 percent to an annual increase of 17 percent, there was an overall increase of 7 percent over the eleven-year period due to an overall increase in harvested area.[3]

The factors that affect the rice acreage in any year vary from state to state, although the price of rice relative to competing crops is the primary controlling variable in most states. Price is the primary factor affecting rice area in Arkansas, as farmers will plant more of what is most lucrative amongst soybeans, rice, and cotton. Government support programs have also been influential in so much as they affect the price received for a rice crop (Slaton 2001b, Mayhew 1997). California rice area is primarily influenced by price and government programs, but is also affected by water availability (Mutters 2001). In Florida, the state having the smallest harvested rice area, rice acreage is largely a function of the price of rice relative to sugarcane and corn. Most rice in Florida is rotated with sugarcane, but sometimes it is more profitable for farmers to follow their sugarcane crop with sweet corn or more sugarcane instead of rice (Schueneman 1997, 2001b). In Louisiana, rice area is influenced by government support programs, the price of rice relative to cotton, soybeans, and corn, and in some years, weather (Saichuk 1997, Linscombe 2001b). For example, a drought in 2000 caused extensive saltwater intrusion along the Gulf Coast, making over 32,000 hectares unplantable. In Mississippi, rice is usually rotated with soybeans, but if soybean prices increase relative to rice prices, then some of the acreage that would have been planted in rice, is instead planted in soybeans (Street 1997, 2001). In Missouri, rice acreage is affected by weather (e.g., rain during the planting season may prevent the planting of rice), the price differential between rice and soybeans or cotton, and government support programs (Stevens 1997, Guethle 2001). In Texas, rice area is affected mainly by the price of rice, government support programs, and water availability (Klosterboer 1997, 2001b).

---

[2] The roots of rice plants shed organic material, which is referred to as "root exudate." The amount of root exudate produced by a rice plant over a growing season varies among rice varieties.

[3] The 11 percent decrease occurred between 1992 and 1993; the 17 percent increase happened between 1993 and 1994.

Table 5-7: CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq.)

State	1990		1995	1996	1997	1998	1999	2000	2001
Primary	**5.1**		**5.6**	**5.0**	**5.6**	**5.8**	**6.3**	**5.5**	**5.9**
Arkansas	2.1		2.4	2.1	2.5	2.7	2.9	2.5	2.9
California	0.7		0.8	0.9	0.9	0.8	0.9	1.0	0.8
Florida	+		+	+	+	+	+	+	+
Louisiana	1.0		1.0	1.0	1.0	1.1	1.1	0.9	1.0
Mississippi	0.4		0.5	0.4	0.4	0.5	0.6	0.4	0.5
Missouri	0.1		0.2	0.2	0.2	0.3	0.3	0.3	0.4
Texas	0.6		0.6	0.5	0.5	0.5	0.5	0.4	0.4
Ratoon	**2.1**		**2.1**	**1.9**	**1.9**	**2.1**	**2.0**	**2.0**	**1.7**
Arkansas	0.0		0.0	0.0	0.0	+	+	0.0	0.0
Florida	+		0.1	0.1	0.1	0.1	0.1	0.1	+
Louisiana	1.1		1.1	1.1	1.2	1.2	1.2	1.3	1.1
Texas	0.9		0.8	0.8	0.7	0.8	0.7	0.7	0.6
Total	**7.1**		**7.6**	**7.0**	**7.5**	**7.9**	**8.3**	**7.5**	**7.6**

+ Less than 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 5-8: CH_4 Emissions from Rice Cultivation (Gg)

State	1990		1995	1996	1997	1998	1999	2000	2001
Primary	**241**		**265**	**240**	**265**	**278**	**300**	**260**	**283**
Arkansas	102		114	99	118	126	138	120	138
California	34		40	43	44	39	43	47	40
Florida	1		2	2	2	2	2	2	1
Louisiana	46		48	45	50	53	52	41	46
Mississippi	21		25	18	20	23	28	19	22
Missouri	7		10	8	10	12	16	14	18
Texas	30		27	25	22	24	22	18	18
Ratoon	**98**		**98**	**92**	**91**	**98**	**95**	**97**	**81**
Arkansas	0		0	0	0	+	+	0	0
Florida	2		4	4	3	3	4	3	2
Louisiana	52		54	51	55	59	58	61	52
Texas	45		40	38	33	36	33	34	27
Total	**339**		**363**	**332**	**356**	**376**	**395**	**357**	**364**

+ Less than 0.5 Gg
Note: Totals may not sum due to independent rounding.

Methodology

The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) recommends utilizing harvested rice areas and area-based seasonally integrated emission factors (i.e., amount of CH_4 emitted over a growing season per unit harvested area) to estimate annual CH_4 emissions from rice cultivation. This methodology is followed with the use of United States-specific emission factors derived from rice field measurements. Seasonal emissions have been found to be much higher for ratooned crops than for primary crops, so emissions from ratooned and primary areas are estimated separately using emission factors that are representative of the particular growing season. This is consistent with IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000).

Data Sources

The harvested rice areas for the primary and ratoon crops in each state are presented in Table 5-9. Primary crop areas for 1990 through 2001 for all states except Florida were taken from U.S. Department of Agriculture's *Field Crops Final Estimates 1987-1992* (USDA 1994), *Field Crops Final Estimates 1992-1997* (USDA 1998), *Crop Production 2000 Summary* (USDA 2001), and *Crop Production 2001 Summary* (USDA 2002). Harvested rice areas in Florida, which are not reported by USDA, were obtained from Tom Schueneman (1999b, 1999c, 2000, 2001a), a Florida agricultural extension agent, and Dr. Chris Deren (2002) of the Everglades Research and Education Centre at the University of Florida. Acreages for the ratoon crops were derived from conversations with the agricultural extension agents in each state. In Arkansas, ratooning occurred only in 1998 and 1999, when the ratooned area was less than 1 percent of the primary area (Slaton 1999, 2000, 2001a). In Florida, the ratooned area was 50 percent of the primary area from 1990 to 1998 (Schueneman 1999a), about 65 percent of the primary area in 1999 (Schueneman 2000), around 41 percent of the primary area in 2000 (Schueneman 2001a), and about 70 percent of the primary area in 2001(Deren 2002). In Louisiana, the percentage of the primary area that was ratooned was constant at 30 percent over the 1990 to 1999 period, but increased to approximately 40 percent in 2000, before returning to 30 percent in 2001 (Linscombe 1999a, 2001a, 2002 and Bollich 2000). In Texas, the percentage of the primary area that was ratooned was constant at 40 percent over the entire 1990 to 1999 period and in 2001, but increased to 50 percent in 2000 due to an early primary crop (Klosterboer 1999, 2000, 2001a, 2002).

To determine what seasonal CH_4 emission factors should be used for the primary and ratoon crops, CH_4 flux information from rice field measurements in the United States was collected. Experiments which involved the application of nitrate or sulfate fertilizers, or other substances believed to suppress CH_4 formation, as well as experiments in which measurements were not made over an entire flooding season or in which floodwaters were drained mid-season, were excluded from the analysis. The remaining experimental results[4] were then sorted by season (i.e., primary and ratoon) and type of fertilizer amendment (i.e., no fertilizer added, organic fertilizer added, and synthetic and organic fertilizer added). The experimental results from primary crops with synthetic and organic fertilizer added (Bossio et al. 1999, Cicerone et al. 1992, Sass et al. 1991a and 1991b) were averaged to derive an emission factor for the primary crop, and the experimental results from ratoon crops with synthetic fertilizer added (Lindau and Bollich 1993, Lindau et al. 1995) were averaged to derive an emission factor for the ratoon crop. The resultant emission factor for the primary crop is 210 kg CH_4/hectare-season, and the resultant emission factor for the ratoon crop is 780 kg CH_4/hectare-season.

Table 5-9: Rice Areas Harvested (Hectares)

State/Crop	1990		1995	1996	1997	1998	1999	2000	2001
Arkansas									
Primary	485,633		542,291	473,493	562,525	600,971	657,628	570,619	656,010
Ratoon*	NO		NO	NO	NO	202	202	NO	NO
California	159,854		188,183	202,347	208,822	185,350	204,371	221,773	190,611
Florida									
Primary	4,978		9,713	8,903	7,689	8,094	7,229	7,801	4,562
Ratoon	2,489		4,856	4,452	3,845	4,047	4,673	3,193	2,752
Louisiana									
Primary	220,558		230,676	215,702	235,937	250,911	249,292	194,253	220,963
Ratoon	66,168		69,203	64,711	70,781	75,273	74,788	77,701	66,289
Mississippi	101,174		116,552	84,176	96,317	108,458	130,716	88,223	102,388
Missouri	32,376		45,326	38,446	47,349	57,871	74,464	68,393	83,772
Texas									
Primary	142,857		128,693	120,599	104,816	114,529	104,816	86,605	87,414
Ratoon	57,143		51,477	48,240	41,926	45,811	41,926	43,302	34,966
Total	**1,273,229**		**1,386,969**	**1,261,068**	**1,380,008**	**1,451,518**	**1,550,106**	**1,361,864**	**1,449,726**

* Arkansas ratooning occurred only in 1998 and 1999.
NO (Not Occurring)
Note: Totals may not sum due to independent rounding.

[4] In some of these remaining experiments, measurements from individual plots were excluded from the analysis because of the reasons just mentioned. In addition, one measurement from the ratooned fields (i.e., the flux of 2.041 g/m^2/day in Lindau and Bollich 1993) was excluded since this emission rate is unusually high compared to other flux measurements in the United States, as well as in Europe and Asia (IPCC/UNEP/OECD/IEA 1997).

Uncertainty

The largest uncertainty in the calculation of CH_4 emissions from rice cultivation is associated with the emission factors. Seasonal emissions, derived from field measurements in the United States, vary by more than one order of magnitude. This variability is due to differences in cultivation practices, particularly the type, amount, and mode of fertilizer application; differences in cultivar type; and differences in soil and climatic conditions. Some of this variability is accounted for by separating primary from ratooned areas. However, even within a cropping season, measured emissions vary significantly. Of the experiments that were used to derive the emission factors used here, primary emissions ranged from 22 to 479 kg CH_4/hectare-season and ratoon emissions ranged from 481 to 1,490 kg CH_4/hectare-season. Based on these emission ranges, total CH_4 emissions from rice cultivation in 2001 were estimated to range from 1.7 to 17 Tg CO_2 Eq. (80 to 800 Gg).

A second source of uncertainty is the ratooned area data, which are not compiled regularly. However, this is a relatively minor source of uncertainty, as these areas account for less than 10 percent of the total area. Expert judgment was used to estimate these areas.

The last source of uncertainty is in the practice of flooding outside of the normal rice season. According to agriculture extension agents, all of the rice-growing states practice this on some part of their rice acreage. Estimates of these areas range from 5 to 68 percent of the rice acreage. Fields are flooded for a variety of reasons: to provide habitat for waterfowl, to provide ponds for crawfish production, and to aid in rice straw decomposition. To date, CH_4 flux measurements have not been undertaken in all of these states or under all representative conditions, so this activity is not included in the emission estimates presented here.

Agricultural Soil Management

Nitrous oxide is produced naturally in soils through the microbial processes of nitrification and denitrification.[5] A number of agricultural activities add nitrogen to soils, thereby increasing the amount of nitrogen available for nitrification and denitrification, and ultimately the amount of N_2O emitted. These activities may add nitrogen to soils either directly or indirectly (Figure 5-2). Direct additions occur through various soil management practices and from the deposition of manure on soils by animals on pasture, range, and paddock (i.e., by animals whose manure is not managed). Soil management practices that add nitrogen to soils include fertilizer use, application of managed livestock manure and sewage sludge, production of nitrogen-fixing crops, retention of crop residues, and cultivation of histosols (i.e., soils with a high organic matter content, otherwise known as organic soils).[6] Indirect additions of nitrogen to soils occur through two mechanisms: 1) volatilization and subsequent atmospheric deposition of applied nitrogen;[7] and 2) surface runoff and leaching of applied nitrogen into groundwater and surface water. Other agricultural soil management, such as irrigation, drainage, tillage practices, and fallowing of land, can affect fluxes of N_2O, as well as other greenhouse gases, to and from soils. However, because there are significant uncertainties associated with these other fluxes, they have not been estimated.

---

[5] Nitrification and denitrification are two processes within the nitrogen cycle that are brought about by certain microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH_4) to nitrate (NO_3), and denitrification is the anaerobic microbial reduction of nitrate to dinitrogen gas (N_2). Nitrous oxide is a gaseous intermediate product in the reaction sequence of denitrification, which leaks from microbial cells into the soil and then into the atmosphere. Nitrous oxide is also produced during nitrification, although by a less well understood mechanism (Nevison 2000).

[6] Cultivation of histosols does not, *per se*, "add" nitrogen to soils. Instead, the process of cultivation enhances mineralization of nitrogen-rich organic matter that is present in histosols, thereby enhancing N_2O emissions from histosols.

[7] These processes entail volatilization of applied nitrogen as ammonia (NH_3) and oxides of nitrogen (NO_x), transformations of these gases within the atmosphere (or upon deposition), and deposition of the nitrogen primarily in the form of particulate ammonium (NH_4), nitric acid (HNO_3), and oxides of nitrogen.

Figure 5-2: Direct and Indirect N_2O Emissions from Agricultural Soils

Agricultural soil management is the largest source of N_2O in the United States.[8] Estimated emissions from this source in 2001 were 294.3 Tg CO_2 Eq. (949 Gg N_2O) (see Table 5-10 and Table 5-11). Although annual agricultural soil management emissions fluctuated between 1990 and 2001, there was a general increase in emissions over the twelve-year period (see Annex N for a complete time series of emission estimates). This general increase in emissions was due primarily to an increase in synthetic fertilizer use, manure production, and crop and forage production over this period. The year-to-year fluctuations are largely a reflection of annual variations in synthetic fertilizer consumption and crop production. Over the twelve-year period, total emissions of N_2O from agricultural soil management increased by approximately 10 percent.

Table 5-10: N_2O Emissions from Agricultural Soil Management (Tg CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000	2001
Direct	**193.7**	**205.1**	**212.6**	**217.8**	**219.0**	**216.8**	**215.9**	**216.6**
Managed Soils	153.3	161.5	169.1	175.6	177.6	175.9	175.6	176.7
Pasture, Range, & Paddock Livestock	40.4	43.6	43.5	42.2	41.3	40.9	40.3	39.9
Indirect	**73.8**	**79.0**	**80.6**	**80.3**	**80.2**	**80.2**	**78.7**	**77.7**
Total	**267.5**	**284.1**	**293.2**	**298.2**	**299.2**	**297.0**	**294.6**	**294.3**

Note: Totals may not sum due to independent rounding.

Table 5-11: N_2O Emissions from Agricultural Soil Management (Gg)

Activity	1990	1995	1996	1997	1998	1999	2000	2001
Direct	**625**	**662**	**685**	**703**	**706**	**700**	**696**	**699**
Managed Soils	495	521	545	567	573	568	566	570
Pasture, Range, & Paddock Livestock	130	141	140	136	133	132	130	129
Indirect	**238**	**255**	**260**	**259**	**259**	**259**	**254**	**251**
Total	**863**	**916**	**946**	**962**	**965**	**958**	**950**	**949**

Note: Totals may not sum due to independent rounding.

Estimated direct and indirect N_2O emissions, by subsource, are provided in Table 5-12, Table 5-13, and Table 5-14.

Table 5-12: Direct N_2O Emissions from Managed Soils (Tg CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000	2001
Commercial Fertilizers*	55.4	59.2	61.2	61.3	61.4	61.6	59.8	58.6
Livestock Manure	13.0	13.6	13.7	14.0	14.2	14.2	14.4	14.5
Sewage Sludge	0.4	0.6	0.6	0.7	0.7	0.7	0.7	0.7
N Fixation	58.5	61.8	63.9	68.2	69.2	68.2	68.8	70.6
Crop Residue	23.2	23.4	26.8	28.7	29.3	28.3	29.0	29.3
Histosol Cultivation	2.8	2.8	2.8	2.9	2.9	2.9	2.9	2.9
Total	**153.3**	**161.5**	**169.1**	**175.6**	**177.6**	**175.9**	**175.6**	**176.6**

Note: Totals may not sum due to independent rounding.
* Excludes sewage sludge and livestock manure used as commercial fertilizers.

Table 5-13: Direct N_2O Emissions from Pasture, Range, and Paddock Livestock Manure (Tg CO_2 Eq.)

Animal Type	1990	1995	1996	1997	1998	1999	2000	2001

[8] Note that the emission estimates for this source category include applications of nitrogen to *all* soils (e.g., forest soils, urban areas, golf courses, etc.), but the term "Agricultural Soil Management" is kept for consistency with the reporting structure of the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Beef Cattle	35.2	38.9	39.0	37.8	37.0	36.7	36.0	35.7
Dairy Cows	1.7	1.5	1.4	1.3	1.3	1.2	1.2	1.2
Swine	0.5	0.3	0.3	0.2	0.2	0.2	0.2	0.2
Sheep	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Goats	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Poultry	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Horses	2.2	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Total	**40.4**	**43.6**	**43.5**	**42.2**	**41.3**	**40.9**	**40.3**	**39.9**

Note: Totals may not sum due to independent rounding.

Table 5-14: Indirect N_2O Emissions (Tg CO_2 Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000	2001
Volatilization & Atm. Deposition	**11.7**	**12.5**	**12.7**	**12.6**	**12.6**	**12.6**	**12.4**	**12.3**
Commercial Fertilizers*	4.9	5.3	5.4	5.4	5.5	5.5	5.3	5.2
Livestock Manure	6.7	7.1	7.1	7.1	7.0	7.0	6.9	6.9
Sewage Sludge	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Surface Leaching & Runoff	**62.1**	**66.5**	**67.9**	**67.7**	**67.6**	**67.6**	**66.3**	**65.4**
Commercial Fertilizers*	36.9	39.5	40.8	40.9	40.9	41.1	39.9	39.1
Livestock Manure	24.9	26.5	26.6	26.3	26.1	26.0	25.9	25.8
Sewage Sludge	0.3	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Total	**73.8**	**79.0**	**80.6**	**80.3**	**80.2**	**80.2**	**78.7**	**77.7**

Note: Totals may not sum due to independent rounding.
* Excludes sewage sludge and livestock manure used as commercial fertilizers.

Methodology

The methodology used to estimate emissions from agricultural soil management is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), as amended by the IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000). The *Revised 1996 IPCC Guidelines* divide this N_2O source category into three components: (1) direct emissions from managed soils due to applied nitrogen and cultivation of histosols; (2) direct emissions from soils due to the deposition of manure by livestock on pasture, range, and paddock; and (3) indirect emissions from soils induced by applied fertilizers, sewage sludge and total livestock manure nitrogen.

Annex N provides more detailed information on the methodologies and data used to calculate N_2O emissions from each of these three components.

Direct N_2O Emissions from Managed Soils

Direct N_2O emissions from managed soils are composed of two parts, which are estimated separately and then summed. These two parts are 1) emissions due to nitrogen applications, and 2) emissions from histosol cultivation.

Estimates of direct N_2O emissions from nitrogen applications were based on the total amount of nitrogen that is applied to soils annually through the following practices: (a) the application of synthetic and organic commercial fertilizers, (b) the application of livestock manure through both daily spread operations and through the eventual application of manure that had been stored in manure management systems, (c) the application of sewage sludge, (d) the production of nitrogen-fixing crops and forages, and (e) the retention of crop residues (i.e., leaving residues in the field after harvest). For each of these practices, the annual amounts of nitrogen applied were estimated as follows:

a) Synthetic and organic commercial fertilizer nitrogen applications were derived from annual fertilizer consumption data and the nitrogen content of the fertilizers.

b) Livestock manure nitrogen applications were based on the assumption that all livestock manure is applied to soils except for two components: 1) a small portion of poultry manure that is used as a livestock feed supplement, and 2) the manure from pasture, range, and paddock livestock. The manure nitrogen data were derived from animal population and weight statistics, information on manure management system usage, annual nitrogen excretion rates for each animal type, and information on the fraction of poultry litter that is used as a livestock feed supplement.

c) Sewage sludge nitrogen applications were derived from estimates of annual U.S. sludge production, the nitrogen content of the sludge, and periodic surveys of sludge disposal methods.

d) The amounts of nitrogen made available to soils through the cultivation of nitrogen-fixing crops and forages were based on estimates of the amount of nitrogen in aboveground plant biomass, which were derived from annual crop production statistics, mass ratios of aboveground residue to crop product, dry matter fractions, and nitrogen contents of the plant biomass.

e) Crop residue nitrogen retention data were derived from information about which residues are typically left on the field, the fractions of residues left on the field, annual crop production statistics, mass ratios of aboveground residue to crop product, and dry matter fractions and nitrogen contents of the residues.

After the annual amounts of nitrogen applied were estimated for each practice, each amount of nitrogen was reduced by the fraction that is assumed to volatilize according to the *Revised 1996 IPCC Guidelines* and the IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. The net amounts left on the soil from each practice were then summed to yield total unvolatilized applied nitrogen, which was multiplied by the IPCC default emission factor for nitrogen applications.

Estimates of annual N_2O emissions from histosol cultivation were based on estimates of the total U.S. acreage of histosols cultivated annually for each of two climatic zones: 1) temperate, and 2) sub-tropical. To estimate annual emissions, the total temperate area was multiplied by the IPCC default emission factor for temperate regions, and the total sub-tropical area was multiplied by the average of the IPCC default emission factors for temperate and tropical regions.[9]

Total annual emissions from nitrogen applications, and annual emissions from histosol cultivation, were then summed to estimate total direct emissions from managed soils.

Direct N_2O Emissions from Pasture, Range, and Paddock Livestock Manure

Estimates of N_2O emissions from this component are based on the amount of nitrogen in the manure that is deposited annually on soils by livestock in pasture, range, and paddock. Estimates of annual manure nitrogen from these livestock were derived from animal population and weight statistics; information on the fraction of the total population of each animal type that is on pasture, range, or paddock; and annual nitrogen excretion rates for each animal type. The annual amounts of manure nitrogen from each animal type were summed over all animal types to yield total pasture, range, and paddock manure nitrogen, which was then multiplied by the IPCC default emission factor for pasture, range, and paddock nitrogen to estimate N_2O emissions.

Indirect N_2O Emissions from Soils

Indirect emissions of N_2O are composed of two parts, which are estimated separately and then summed. These two parts are 1) emissions resulting from volatilization and subsequent deposition of the nitrogen in applied fertilizers,

---

[9] Note that the IPCC default emission factors for histosols have been revised in the IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000). These revised default emission factors (IPCC 2000) were used in these calculations.

applied sewage sludge, and all livestock manure,[10] and 2) leaching and runoff of nitrogen in applied fertilizers, applied sewage sludge, and applied plus deposited livestock manure. The activity data (i.e., nitrogen in applied fertilizers, applied sewage sludge, all livestock manure, and applied plus deposited livestock manure) were estimated in the same way as for the direct emission estimates.

To estimate the annual amount of applied nitrogen that volatilizes, the annual amounts of applied synthetic fertilizer nitrogen, applied sewage sludge nitrogen, and all livestock manure nitrogen, were each multiplied by the appropriate IPCC default volatilization fraction. The three amounts of volatilized nitrogen were then summed, and the sum was multiplied by the IPCC default emission factor for volatilized/deposited nitrogen.

To estimate the annual amount of nitrogen that leaches or runs off, the annual amounts of applied synthetic fertilizer nitrogen, applied sewage sludge nitrogen, and applied plus deposited livestock manure nitrogen were each multiplied by the IPCC default leached/runoff fraction. The three amounts of leached/runoff nitrogen were then summed, and the sum was multiplied by the IPCC default emission factor for leached/runoff nitrogen.

Total annual indirect emissions from volatilization, and annual indirect emissions from leaching and runoff, were then summed to estimate total indirect emissions of N_2O from managed soils.

Data Sources

The activity data used in these calculations were obtained from numerous sources. Annual synthetic and organic fertilizer consumption data for the United States were obtained from annual publications on commercial fertilizer statistics (TVA 1991, 1992a, 1993, 1994; AAPFCO 1995, 1996, 1997, 1998, 1999, 2000b, 2002). Fertilizer nitrogen contents were taken from these same publications and AAPFCO (2000a). Livestock population data were obtained from USDA publications (USDA 1994b,c; 1995a,b; 1998a,c; 1999a-e; 2000a-g; 2001b-g; 2002b-g), the FAOSTAT database (FAO 2002), and Lange (2000). Manure management information was obtained from Poe et al. (1999), Safley et al. (1992), and personal communications with agricultural experts (Anderson 2000, Deal 2000, Johnson 2000, Miller 2000, Milton 2000, Stettler 2000, Sweeten 2000, Wright 2000). Livestock weight data were obtained from Safley (2000), USDA (1996, 1998d), and ASAE (1999); daily rates of nitrogen excretion from ASAE (1999) and USDA (1996); and information about the fraction of poultry litter used as a feed supplement from Carpenter (1992). Data collected by the EPA were used to derive annual estimates of land application of sewage sludge (EPA 1993, 1999). The nitrogen content of sewage sludge was taken from Metcalf and Eddy, Inc. (1991). Annual production statistics for nitrogen-fixing crops were obtained from USDA reports (USDA 1994a, 1998b, 2000i, 2001a, 2002a), a book on forage crops (Taylor and Smith 1995, Pederson 1995, Beuselinck and Grant 1995, Hoveland and Evers 1995), and personal communications with forage experts (Cropper 2000, Gerrish 2000, Hoveland 2000, Evers 2000, and Pederson 2000). Mass ratios of aboveground residue to crop product, dry matter fractions, and nitrogen contents for nitrogen-fixing crops were obtained from Strehler and Stützle (1987), Barnard and Kristoferson (1985), Karkosh (2000), Ketzis (1999), and IPCC/UNEP/OECD/IEA (1997). Annual production statistics for crops whose residues are left on the field, except for rice in Florida, were obtained from USDA reports (USDA 1994a, 1998b, 2000i, 2001a, 2002a). Production statistics for rice in Florida are not recorded by USDA, so these were derived from Smith (1999), Schueneman (1999, 2001), and Deren (2002). Aboveground residue to crop mass ratios, residue dry matter fractions, and residue nitrogen contents were obtained from Strehler and Stützle (1987), Turn et al. (1997), Ketzis (1999), and Barnard and Kristoferson (1985). Estimates of the fractions of residues left on the field were based on information provided by Karkosh (2000), and on information about rice residue burning (see the Agricultural Residue Burning section). The annual areas of cultivated histosols were estimated from 1982, 1992, and 1997 statistics in USDA's *1997 National Resources Inventory* (USDA 2000h, as extracted by Eve 2001, and revised by Ogle 2002).

---

[10] Total livestock manure nitrogen is used in the calculation of indirect N_2O emissions from volatilization because all manure nitrogen, regardless of how the manure is managed or used, is assumed to be subject to volatilization.

All emission factors[11], volatilization fractions, and the leaching/runoff fraction were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), as amended by the IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000).

Uncertainty

The amount of N_2O emitted from managed soils depends not only on N inputs, but also on a large number of variables, including organic carbon availability, O_2 partial pressure, soil moisture content, pH, soil temperature, and soil amendment management practices. However, the effect of the combined interaction of these other variables on N_2O flux is complex and highly uncertain. Therefore, the IPCC default methodology, which is used here, is based only on N inputs and does not utilize these other variables. As noted in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), this is a generalized approach that treats all soils, except cultivated histosols, as being under the same conditions. The estimated ranges around the IPCC default emission factors provide an indication of the uncertainty in the emission estimates due to this simplified methodology. Most of the emission factor ranges are about an order of magnitude, or larger. Developing an emission estimation methodology that explicitly utilizes these other variables will require more scientific research and much more detailed databases, and will likely involve the use of process models (see Box 5-1).

Uncertainties also exist in the activity data used to derive emission estimates. In particular, the fertilizer statistics include only those organic fertilizers that enter the commercial market, so non-commercial fertilizers (other than the estimated manure and crop residues) have not been captured. The livestock excretion values, while based on detailed population and weight statistics, were derived using simplifying assumptions concerning the types of management systems employed. Statistics on sewage sludge applied to soils were not available on an annual basis; annual production and application estimates were based on figures and projections that were calculated from surveys that yielded uncertainty levels as high as 14 percent (Bastian 1999). Annual data were obtained by interpolating and extrapolating at constant rates from these uncertain figures, though change between the years was unlikely to be constant (Bastian 2001). The production statistics for the nitrogen-fixing crops that are forage legumes are highly uncertain because statistics are not compiled for any of these crops except alfalfa, and the alfalfa statistics include alfalfa mixtures. Conversion factors for the nitrogen-fixing crops were based on a limited number of studies, and may not be representative of all conditions in the United States. Data on crop residues left on the field are not available, so expert judgment was used to estimate the amount of residues left on soils. And finally, the estimates of cultivated histosol areas are uncertain because they are from a natural resource inventory that was not explicitly designed as a soil survey, and this natural resource inventory contains data for only three years (1982, 1992, and 1997). Annual histosol areas were estimated by linear interpolation and extrapolation.

[BEGIN BOX]

Box 5-1: DAYCENT Model Estimates of N_2O Emissions from Agricultural Soils

The U.S. EPA is currently working in collaboration with the Agricultural Research Service and the Natural Resource Ecology Lab at Colorado State University to test the feasibility of using the DAYCENT ecosystem process model to estimate N_2O emissions from agricultural soil management. In countries like the United States that cover large land areas and have a diversity of climate, soils, land use and management systems, the use of an ecosystem process model such as DAYCENT can have great advantages over the single emission factor approach as specified in the IPCC Guidelines for estimating N_2O emissions. Potential advantages of a dynamic simulation based approach include the ability to use actual observed weather, observed annual crop yields, and more detailed soils and management information to drive the estimates of N_2O emissions. One of the greatest challenges involved in this effort will be obtaining the activity data (e.g., synthetic fertilizer and manure nitrogen inputs) at the appropriate spatial scale for use in the DAYCENT model. The goal of the modeling effort is to develop county-level estimates

---

[11] Note that the emission factor used for cultivated histosols in the sub-tropics is the average of the tropical and temperate default IPCC emission factors.

of N_2O emissions from agricultural soils that can be summed to produce a national-level estimate. Emission estimates from this modeling effort are intended for use in the 1990-2002 inventory.

[END BOX]

Field Burning of Agricultural Residues

Large quantities of agricultural crop residues are produced by farming activities. There are a variety of ways to dispose of these residues. For example, agricultural residues can be left on or plowed back into the field, composted and then applied to soils, landfilled, or burned in the field. Alternatively, they can be collected and used as fuel, animal bedding material, or supplemental animal feed. Field burning of crop residues is not considered a net source of CO_2 because the carbon released to the atmosphere as CO_2 during burning is assumed to be reabsorbed during the next growing season. Crop residue burning is, however, a net source of CH_4, N_2O, CO, and NO_x, which are released during combustion.

Field burning is not a common method of agricultural residue disposal in the United States; therefore, emissions from this source are minor. The primary crop types whose residues are typically burned in the United States are wheat, rice, sugarcane, corn, barley, soybeans, and peanuts. Of these residues, less than 5 percent is burned each year, except for rice.[12] Annual emissions from this source over the period 1990 through 2001 averaged approximately 0.7 Tg CO_2 Eq. (35 Gg) of CH_4, 0.4 Tg CO_2 Eq. (1 Gg) of N_2O, 728 Gg of CO, and 32 Gg of NO_x (see Table 5-15 and Table 5-16).

Table 5-15: Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq.)

Gas/Crop Type	1990		1995	1996	1997	1998	1999	2000	2001
CH_4	**0.7**		**0.7**	**0.7**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**
Wheat	0.1		0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rice	0.1		0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sugarcane	+		+	+	+	+	+	+	+
Corn	0.3		0.3	0.3	0.3	0.3	0.3	0.4	0.3
Barley	+		+	+	+	+	+	+	+
Soybeans	0.1		0.2	0.2	0.2	0.2	0.2	0.2	0.2
Peanuts	+		+	+	+	+	+	+	+
N_2O	**0.4**		**0.4**	**0.4**	**0.4**	**0.5**	**0.4**	**0.5**	**0.5**
Wheat	+		+	+	+	+	+	+	+
Rice	+		+	+	+	+	+	+	+
Sugarcane	+		+	+	+	+	+	+	+
Corn	0.1		0.1	0.1	0.1	0.1	0.1	0.1	0.1
Barley	+		+	+	+	+	+	+	+
Soybeans	0.2		0.2	0.2	0.3	0.3	0.3	0.3	0.3
Peanuts	+		+	+	+	+	+	+	+
Total	**1.1**		**1.0**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 5-16: Emissions from Field Burning of Agricultural Residues (Gg)*

Gas/Crop Type	1990		1995	1996	1997	1998	1999	2000	2001
CH_4	**33**		**31**	**36**	**36**	**37**	**36**	**37**	**36**

[12] The fraction of rice straw burned each year is significantly higher than that for other crops (see "Data Sources" discussion below).

Wheat	7	5	5	6	6	5	5	5
Rice	4	4	4	3	3	3	3	3
Sugarcane	1	1	1	1	1	1	1	1
Corn	13	13	16	16	17	16	17	16
Barley	1	1	1	1	1	+	1	+
Soybeans	7	8	9	10	10	10	10	11
Peanuts	+	+	+	+	+	+	+	+
N_2O	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Wheat	+	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+	+
Soybeans	1	1	1	1	1	1	1	1
Peanuts	+	+	+	+	+	+	+	+
CO	**685**	**656**	**747**	**761**	**781**	**760**	**784**	**762**
Wheat	137	109	114	124	128	115	112	98
Rice	81	80	85	66	58	69	69	69
Sugarcane	18	20	19	21	22	23	24	23
Corn	282	263	328	328	347	336	353	338
Barley	16	13	15	13	13	10	12	9
Soybeans	148	167	183	207	211	204	212	222
Peanuts	2	2	2	2	2	2	2	3
NO_x	**28**	**29**	**32**	**34**	**35**	**34**	**35**	**35**
Wheat	4	3	3	3	3	3	3	3
Rice	3	3	3	2	2	2	2	2
Sugarcane	+	+	+	+	+	+	+	+
Corn	7	6	8	8	8	8	8	8
Barley	1	+	+	+	+	+	+	+
Soybeans	14	16	17	20	20	19	20	21
Peanuts	+	+	+	+	+	+	+	+

* Full molecular weight basis.
+ Does not exceed 0.5 Gg
Note: Totals may not sum due to independent rounding.

Methodology

The methodology for estimating greenhouse gas emissions from field burning of agricultural residues is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). In order to estimate the amounts of carbon and nitrogen released during burning, the following equations were used:[13]

Carbon Released = (Annual Crop Production) × (Residue/Crop Product Ratio)
× (Fraction of Residues Burned *in situ*) × (Dry Matter Content of the Residue)
× (Burning Efficiency) × (Carbon Content of the Residue) × (Combustion Efficiency)[14]

[13] Note: As is explained under Data Sources, the fraction of rice residues burned varies among states, so these equations were applied at the state level for rice. These equations were applied at the national level for all other crop types.

[14] Burning Efficiency is defined as the fraction of dry biomass exposed to burning that actually burns. Combustion Efficiency is defined as the fraction of carbon in the fire that is oxidized completely to CO_2. In the methodology recommended by the IPCC, the "burning efficiency" is assumed to be contained in the "fraction of residues burned" factor. However, the number used here to estimate the "fraction of residues burned" does not account for the fraction of exposed residue that does not burn. Therefore, a "burning efficiency factor" was added to the calculations.

Nitrogen Released = (Annual Crop Production) × (Residue/Crop Product Ratio)
× (Fraction of Residues Burned *in situ*) × (Dry Matter Content of the Residue)
× (Burning Efficiency) × (Nitrogen Content of the Residue) × (Combustion Efficiency)

Emissions of CH_4 and CO were calculated by multiplying the amount of carbon released by the appropriate IPCC default emission ratio (i.e., CH_4-C/C or CO-C/C). Similarly, N_2O and NO_x emissions were calculated by multiplying the amount of nitrogen released by the appropriate IPCC default emission ratio (i.e., N_2O-N/N or NO_x-N/N).

Data Sources

The crop residues that are burned in the United States were determined from various state level greenhouse gas emission inventories (ILENR 1993, Oregon Department of Energy 1995, Wisconsin Department of Natural Resources 1993) and publications on agricultural burning in the United States (Jenkins et al. 1992, Turn et al. 1997, EPA 1992).

Crop production data for all crops except rice in Florida were taken from the USDA's *Field Crops, Final Estimates 1987-1992, 1992-1997* (USDA 1994, 1998), *Crop Production 2000 Summary* (USDA 2001), and *Crop Production 2001 Summary* (USDA 2002). Rice production data for Florida, which are not collected by USDA, were estimated by applying average primary and ratoon crop yields for Florida (Smith 1999) to Florida acreages (Schueneman 1999b, 2001; Deren 2002). The production data for the crop types whose residues are burned are presented in Table 5-17.

The percentage of crop residue burned was assumed to be 3 percent for all crops in all years, except rice, based on state inventory data (ILENR 1993, Oregon Department of Energy 1995, Noller 1996, Wisconsin Department of Natural Resources 1993, and Cibrowski 1996). Estimates of the percentage of rice residue burned were derived from state-level estimates of the percentage of rice area burned each year, which were multiplied by state-level, annual rice production statistics. The annual percentages of rice area burned in each state were obtained from the agricultural extension agents in each of the seven rice-producing states and reports of the California Air Resources Boart (CARB) (Bollich 2000; Deren 2002; Guethle 1999, 2000, 2001, 2002; Fife 1999; California Air Resources Board 1999, 2001; Klosterboer 1999a, 1999b, 2000, 2001, 2002; Lindberg 2002; Linscombe 1999a, 1999b, 2001, 2002; Mutters 2002, Najita 2000, 2001; Schueneman 1999a, 1999b, 2001; Slaton 1999a, 1999b, 2000; Street 1999a, 1999b, 2000, 2001, 2002; Wilson 2001, 2002) (see Table 5-18 and Table 5-19). The estimates provided for Arkansas and Florida remained constant over the entire 1990 through 2001 period, while the estimates for all other states varied over the time series. For California, it was assumed that the annual percents of rice area burned in the Sacramento Valley are representative of burning in the entire state, because the Sacramento Valley accounts for over 95 percent of the rice acreage in California (Fife 1999). These percents declined between 1990 and 2001 because of a legislated reduction in rice straw burning (Lindberg 2002) (see Table 5-19).

All residue/crop product mass ratios except sugarcane were obtained from Strehler and Stützle (1987). The datum for sugarcane is from University of California (1977). Residue dry matter contents for all crops except soybeans and peanuts were obtained from Turn et al. (1997). Soybean dry matter content was obtained from Strehler and Stützle (1987). Peanut dry matter content was obtained through personal communications with Jen Ketzis (1999), who accessed Cornell University's Department of Animal Science's computer model, Cornell Net Carbohydrate and Protein System. The residue carbon contents and nitrogen contents for all crops except soybeans and peanuts are from Turn et al. (1997). The residue carbon content for soybeans and peanuts is the IPCC default (IPCC/UNEP/OECD/IEA 1997). The nitrogen content of soybeans is from Barnard and Kristoferson (1985). The nitrogen content of peanuts is from Ketzis (1999). These data are listed in Table 5-20. The burning efficiency was assumed to be 93 percent, and the combustion efficiency was assumed to be 88 percent, for all crop types (EPA 1994). Emission ratios for all gases (see Table 5-21) were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Table 5-17: Agricultural Crop Production (Thousand Metric Tons of Product)

Crop	1990	1995	1996	1997	1998	1999	2000	2001
Wheat	74,292	59,404	61,980	67,534	69,327	62,569	60,758	53,278
Rice	7,105	7,935	7,828	8,339	8,570	9,381	8,697	9,686
Sugarcane	25,525	27,922	26,729	28,766	30,896	32,023	32,762	31,571
Corn*	201,534	187,970	234,518	233,864	247,882	239,549	251,854	241,485
Barley	9,192	7,824	8,544	7,835	7,667	6,103	6,939	5,434
Soybeans	52,416	59,174	64,780	73,176	74,598	72,223	75,055	78,668
Peanuts	1,635	1,570	1,661	1,605	1,798	1,737	1,481	1,923

*Corn for grain (i.e., excludes corn for silage).

Table 5-18: Percentage of Rice Area Burned by State

State	Percent Burned 1990-1998	Percent Burned 1999	Percent Burned 2000	Percent Burned 2001
Arkansas	10	10	10	10
California	variable[a]	27	27	23
Florida[b]	0	0	0	0
Louisiana	6	0	5	4
Mississippi	10	40	40	40
Missouri	5	5	8	5
Texas	1	2	0	0

[a] Values provided in Table 5-19.
[b] Burning of crop residues is illegal in Florida.

Table 5-19: Percentage of Rice Area Burned in California

Year	California
1990	75
1995	59
1996	63
1997	34
1998	33
1999	27
2000	27
2001	23

Table 5-20: Key Assumptions for Estimating Emissions from Agricultural Residue Burning*

Crop	Residue/Crop Ratio	Fraction of Residue Burned	Dry Matter Fraction	Carbon Fraction	Nitrogen Fraction
Wheat	1.3	0.03	0.93	0.4428	0.0062
Rice	1.4	variable	0.91	0.3806	0.0072
Sugarcane	0.8	0.03	0.62	0.4235	0.0040
Corn	1.0	0.03	0.91	0.4478	0.0058
Barley	1.2	0.03	0.93	0.4485	0.0077
Soybeans	2.1	0.03	0.87	0.4500	0.0230
Peanuts	1.0	0.03	0.86	0.4500	0.0106

* The burning efficiency and combustion efficiency for all crops were assumed to be 0.93 and 0.88, respectively.

Table 5-21: Greenhouse Gas Emission Ratios

Gas	Emission Ratio
CH_4[a]	0.005
CO[a]	0.060
N_2O[b]	0.007
NO_x[b]	0.121

[a] Mass of carbon compound released (units of C) relative to mass of total carbon released from burning (units of C).
[b] Mass of nitrogen compound released (units of N) relative to mass of total nitrogen released from burning (units of N).

Uncertainty

The largest source of uncertainty in the calculation of non-CO_2 emissions from field burning of agricultural residues is in the estimates of the fraction of residue of each crop type burned each year. Data on the fraction burned, as well as the gross amount of residue burned each year, are not collected at either the national or state level. In addition, burning practices are highly variable among crops, as well as among states. The fractions of residue burned used in these calculations were based upon information collected by state agencies and in published literature. It is likely that these emission estimates will continue to change as more information becomes available in the future.

Other sources of uncertainty include the residue/crop product mass ratios, residue dry matter contents, burning and combustion efficiencies, and emission ratios. A residue/crop product ratio for a specific crop can vary among cultivars, and for all crops except sugarcane, generic residue/crop product ratios, rather than ratios specific to the United States, have been used. Residue dry matter contents, burning and combustion efficiencies, and emission ratios, all can vary due to weather and other combustion conditions, such as fuel geometry. Values for these variables were taken from literature on agricultural biomass burning.

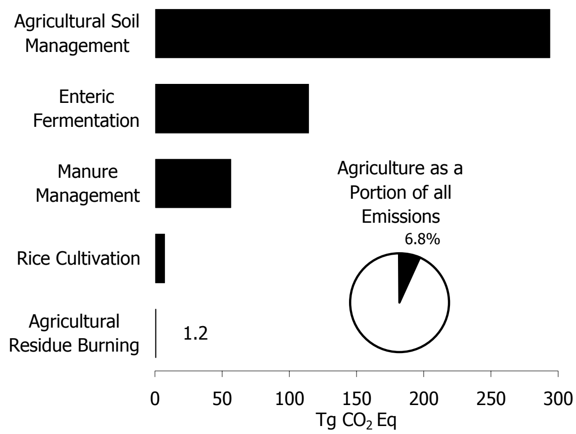
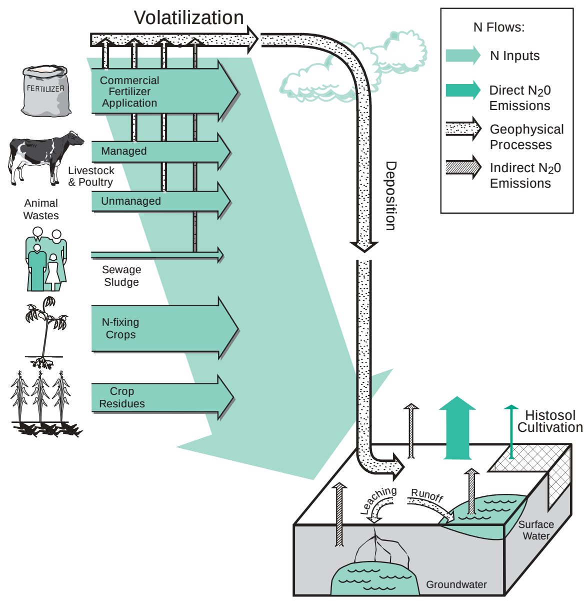


Figure 5-1: 2001 Agriculture Chapter GHG Sources

Figure 5-2

Direct and Indirect N_2O Emissions from Agricultural Soils



This graphic illustrates the sources and pathways of nitrogen that result in direct and indirect N_2O emissions from agricultural soils in the United States. Sources of nitrogen applied to, or deposited on, soils are respresented with arrows on the left-hand side of the graphic. Emissions pathways are also shown with arrows. On the lower right-hand side is a cut-away view of a representative section of a managed soil; histosol cultivation is represented here.